

A FUNCTIONAL PROTOTYPIC INSTRUMENT FOR THE ULTRASONIC MEASUREMENT OF
FORMABILITY (R-BAR, DELTA-R ON STEEL AND TEXTURAL WEIGHTS W400, W420, W440
ON ALUMINUM)

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INTRODUCTION

This paper describes the prototype of a new, state-of-the-art, ultrasonic instrument which has been designed to assess the formability of sheet metals, in particular those properties crucial in deep drawing operations. This instrument was designed and built under the support of the Center for Advanced Technology Development (CATD) of Iowa State University (ISU) through the cooperative efforts of the Center for Nondestructive Evaluation (CNDE) and Ames Laboratory Instrumentation Services Group and MagnaSonics Inc. of Albuquerque, New Mexico.

The primary purpose behind developing a prototypic instrument has been to create a new technology as an alternative to the current industrial techniques for predicting the formability of sheet metals. The conventional techniques (tensile tests, LDR measurements, cupping tests, Modul- \bar{r} , etc.) are destructive and time consuming. The use of ultrasound makes it possible to assess formability rapidly and non-destructively.

The prototypic instrument predicts formability parameters such as the plastic strain ratio and \bar{r} from the results of measurements of the velocity of ultrasonic guided waves propagating at angles of 0,45 and 90 degrees with respect to the rolling direction of the sheet metal. These waves are generated by EMAT (electro-magnetic acoustic transducer) probes switched automatically by the associated controllers via commands from a user interface, touch control screen (TCS). The fact that the EMATs require no couplant, in contrast to piezoelectric transducers, makes the technique particularly suitable for industrial environments. The key element underlying these measurements is the existence of preferred orientation of the grains (crystallographic texture) which is induced in the plate by the rolling process. This crystallographic texture causes a directionality in the plate which affects both the ultrasonic velocities and the formability properties.

The prototypic instrument is a menu-driven automatic measurement instrument. Its unique features, including ease of operation, non-destructive nature and its versatility in measuring both formability parameters and stress (residual and applied), make it a practical and unique tool for an industrial environment.

BACKGROUND

The texture (preferred grain orientation) of a metal polycrystal plays a key role in determining sheet metal formability. For example, under conditions of large scale plastic deformation, one must be concerned about the ease with which this deformation occurs in different directions, information that is important in such operations as the formation of sheet into automotive bodies, airframe parts, and beverage cans. Engineering tests commonly used to predict formability include plastic strain ratio measurements (ratio of in-plane to through-thickness plastic deformation in tensile tests) and earing tests (degree of scalloping of the rim of a cup formed by deep drawing). Considerable progress has been made over the last five years in utilizing ultrasonically obtained texture information in the prediction of these engineering parameters. In a recently completed NBS-Alcoa-Ames collaboration, the possibility of predicting the degree of earing in a deep drawing test has been demonstrated. The availability of an instrument based on these principles would allow one to implement process control procedures to minimize earing and thereby save material. Researchers in Japan and Germany have demonstrated the ability to predict the average formability in steel sheet, and a joint NBS-Ames-Colorado School of Mines project is evaluating this application in the U.S.

The basis of our involvement in these areas has been a set of measurement techniques developed under DOE/BES support. When the grains of a polycrystal are partially aligned, the ultrasonic wave speed will depend on propagation direction because of the anisotropy of the single crystal elastic constants. We have recently shown how to interpret this angular variation in terms of the orientation distribution coefficients. W_{lmn} , which define the texture, and a laboratory mock-up instrument has been developed under the support of the NSF University-Industry Center for NDE. In aluminum applications, the coefficients W_{420} and W_{440} are of greatest interest since they determine the degree of earing that occurs during beverage can formation. In steel sheet applications in the automotive industry, W_{400} is dominant since it controls the average plastic strain ratio, r -bar, a crucial parameter in sheet metal formability analysis. To determine the velocity of each of these parameters, one must know the speed of the waves propagating at 0° , 45° and 90° with respect to the rolling direction of the sheet.

Measurement of stress in metal parts is also quite important. Deleterious consequences of improper stress levels range from catastrophic structural failure to undesired deformation during machining or service. X-ray diffraction technology can monitor stress, but due to penetration limitations, only a very near surface layer ($< 1 \mu\text{m}$ deep) is examined. Ultrasonic approaches are sensitive to stress at greater depths. In essence, these techniques depend on a shift in the ultrasonic wave speed that is proportional to stress. However, the ultrasonic techniques have traditionally found limited application because of competing microstructural influences on the ultrasonic velocity. A procedure recently developed at the Ames Laboratory^[1-5] has overcome that limitation. The solution rests on a measurement of the angular dependence of the velocity of shear waves whose propagation and polarization directions lie in the plane of a part surface. By taking the difference in the velocity of waves propagating in orthogonal directions, one can determine the stress, independent of microstructural considerations. We have recently demonstrated this technique under DOE/BES support and are currently working on a first prototype under the support of the NSF University-Industry Center for NDE. Evaluations of the practicality of these ideas are being conducted at laboratories in the U.S., England, and Germany. Perhaps most noteworthy is a SBIR program, granted by the DOT to MagnaSonics, Inc., to measure the longitudinal force in railroad rail.

The key to practical application of these ideas is the use of couplant-free EMATs to excite and detect the ultrasonic waves. The absence of a requirement for a couplant makes routine use on the shop or mill floor practical and opens the possibility of on-line operations in a real-time process control sense. Commercially purchased EMATs are incorporated in the aforementioned instrumentation projects supported by the NSF University-Industry Center for NDE. To this sensing capability must be added to capability for the rapid and precise measurement of velocity. An optimum combination has been selected for this application.

INSTRUMENT SPECIFICATIONS

Instrument specifications were based on hardware, software and measurement technique developed in the laboratory and on new technology currently in the market place (ie signal processing ICs) not available in our laboratory equipment.

General Description: A "field" instrument to acoustically measure texture and stress on ferrous and non-ferrous metal plate up to 1/8 inch (3.175mm).

Measurement Technique: Differential velocity is measured using two transmitters and one receiver in a fixed linear array of EMAT transducers at 0,45,90 deg. or 0,90 deg. relative rotational directions depending on device configuration:

	Texture	Stress	
Ferrous	0,45,90	0,90	Pulsed Magnets
Non-ferrous	0,45,90	0,90	Permanent Magnets
	So	SHo	

The capability of measuring stress on ferrous plate was not implemented for financial considerations. Stress measurement capability on ferrous plate is reported in [7].

EMAT Driver Frequency: 310-512KHz (nominal)

Sampling Period: 100ns

Time measurement accuracy:

Resolution 0.1ns

Accuracy required for < 2KSI Stress Measurements: Variance 2.5ns

Accuracy required for texture: Variance 10.0ns

W440 < 3.72E-5

W420 < 1.47E-4

W400 < 2.38E-4

MEASUREMENT TECHNIQUE

Plate wave velocity is derived from the difference in time of arrival of RF bursts using two transmitters and one receiver in a fixed linear array of EMAT transducers oriented at 0,45,90 deg. with respect to the rolling direction (the "l" direction) for texture measurements. Stress is similarly measured, but requires only velocities of waves propagating in orthogonal directions. T1 and T2 EMATs are driven in series to

eliminate differential phase shifts due to probe lift-off. A Fourier Transform-Phase-Slope algorithm is used to determine the difference in time of arrival of RF bursts. Measurement cycle time is approximately 4-6 seconds depending on the type of measurements being made. From the measured velocity anisotropy E, E-bar, r-bar, delta r and textural weights W400, W420, and W440 for cubic crystallites are derived. The instrument is capable of making measurements in sheet or plate up to 1/8 inch (3.175mm) with So or SHo velocities ranging from 0.19 to 0.67 cm/us. The first instrument is restricted to cubic materials such as aluminum, copper, brass and steel, however it is possible to incorporate measurements of hexagonal materials such as titanium, zinc, and zirconium in future designs. Future designs could also include greater thicknesses and other geometries.

OPERATOR'S MANUAL

An Operator's Manual [13] was assembled as part of the final field trial marketing phase. The contents include: Introduction, General Information, Installation, Operating Instructions, Physical Principles, Operating Principles and Service. The Operator's Manual contains many diagrams and photographs to illustrate operation and principles. Equations and reference data are also included.

LABORATORY RESULTS

Initial testing was made on sheets that have been "well scrutinized" in the laboratory. A calibration test plate of ferrous steel (ASTM A-366) was chosen from stock steel at the Ames Laboratory. Coupons were made from the same original sheet and sent to Tinius Olsen Testing Machine Co. for measurements using the Modul-r instrument. Tensile measurements were made from additional coupons at the Ames Laboratory. The results of the ultrasonic tensile measurements are within expected errors and are also in good agreement with the Modul-r results as shown below.

Table 1
Ferrous Steel (ASTM A-366) Plate 0.061"

	Texture Instrument	Modul-r	Tensile Test
Velocity (0)	0.55273 cm/us		
Velocity (45)	0.56606 cm/us		
Velocity (90)	0.55803 cm/us		
W400	-1.16E-2		
W420	-9.39E-4		
W440	2.62E-3		
Young's Mod E(0)	30.4 MPsi	30.42 MPsi	
Young's Mod E(45)	33.0 MPsi	33.12 MPsi	
Young's Mod E(90)	30.9 MPsi	31 MPsi	
E-bar	31.8 MPsi	31.92 MPsi	
Delta-E	-2.38 MPsi	-2.407 MPsi	
R-bar	1.52	1.5583	1.5088
Delta-R	0.799	0.8083	0.7570

A comparison of Ultrasonic measurements were also made and compared to Modul-r results on two specimens, one with zinc coating and the other without. This gave a check on the algorithm used to correct for zinc coatings. The algorithm is derived from empirical data studies. The results of the ultrasonic and Modul-r measurements are of the same order as tensile measurement errors as shown below.

Table 2

Ferrous Steel Plate 0.0233"

	Uncoated Sheet	Zinc Coated Sheet	Modul- \bar{r}
Velocity (0)	0.54548 cm/us	0.54331 cm/us	
Velocity (45)	0.55750 cm/us	0.55783 cm/us	
Velocity (90)	0.55025 cm/us	0.55778 cm/us	
W400	-7.25E-3	-6.67E-3	
W420	-8.32E-4	-6.90E-4	
W440	2.33E-3	3.03E-3	
Young's Mod E(0)	30.0 MPsi	29.6 MPsi	30.3 MPsi
Young's Mod E(45)	32.3 MPsi	32.5 MPsi	32.5 MPsi
Young's Mod E(90)	30.5 MPsi	30.0 MPsi	30.55 MPsi
E-bar	31.3 MPsi	31.2 MPsi	31.2 MPsi
Delta-E	-2.08 MPsi	-2.69 MPsi	-2.69 MPsi
R-bar	1.20	1.16*	1.31
Delta-R	0.703	0.901*	0.75

* corrected for zinc coating

FIELD TEST RESULTS

The final phase in the development program was a field trial. Corporations were contacted and agreed that the CATD texture instrument should be demonstrated in their facilities. The field trial was arranged by the SBDC as a dynamic marketing exercise. A prerequisite was an agreement with each host corporation to share data. ISU would measure r-bar on any specimen of steel or the Ws on any specimen of aluminum providing the host company determined tensile r-bar (and if possible Modul-r values of r-bar) on the steel or earing percentages on the aluminum. The ISU measurements were to be performed with the instrument at

Table 3

SHEET	UT	TENSILE	Modul- \bar{r}
ASTM A-366	1.52	1.5088	1.5583
WEIRTON 0233 69	1.20		1.31
COLD ROLLED AKDQ	1.68	1.77	
INTERSTITIAL FREE STEEL	1.84	1.89	
NIPPON BH EXCELITE	1.22	1.17	
SUMITOMO MS 8056	1.91	1.91	
W-P* Sample #1 HR	0.92	0.91	
W-P Sample #2 HR	0.89	0.91	
W-P Sample #3 HR	0.95	0.91	
W-P Sample #4 CR	1.84	1.81	
W-P Sample #5 CR	1.52	1.49	
W-P Sample #6 CR	1.65	1.65	
W-P Sample #7 CR	1.55	1.55	
W-P Sample #8 CR,GAL	1.57	1.50	
W-P Sample #9 CR,GAL	1.06	1.17	
W-P Sample #10 CR,GAL	1.61	1.53	
W-P Sample #13 CR	1.57	1.62	
W-P Sample #14 CR	1.18	1.11	
W-P Sample #15 E.Sn	1.64	1.59	

* Wheeling-Pittsburgh

the metal manufacturers' or users' facilities with audiences of their choosing. At the time of this publication only part of the manufacturer's measurements are available. Those results are shown below. In all cases the ultrasonic measurements are of the same order of magnitude as errors in tensile measurement errors and are also in good agreement with the Modul-r data. It is expected that the remaining data will prove just as successful.

CONCLUSIONS

An industrial-quality manufacturable automatic instrument has been developed, built, and tested to measure textural parameters in metal sheet. The texture parameters are used in industry to predict drawability of the sheet into such end items as beverage cans, propane tanks, and automotive parts. The new instrument employs EMAT ultrasonic technology which is non-contacting, nondestructive, applicable to cubic metal, and independent of zinc coatings. This technology presents the potential for testing coils of sheet at many points along their length and width. This capability is in contrast to previous methods which were destructive and required cutting specimens only from the end of a coil. The new technology embodied in the instrument will permit the instrument to be used on moving sheet metal as on rolling lines, annealing lines, rerolling inspection lines, and blanking lines for process control and quality assurance. However, building probes and fixturing to operate on a fast-moving line in a factory was beyond the funding which produced this instrument. The probes built work on stationary flat sheet in a factory environment or in a laboratory. Typical installations would be next to a press line to audit blank for deep-drawn parts and in a slitting operation to audit coils before they are slit into narrow strip for beverage can blanks. For this environment, the instrument has cooling, EMI immunity, shock mounted casters, and other features permitting operation in a factory.

The instrument was designed, built, and tested by an interdisciplinary team of scientists, engineers, technicians, and market researchers under matrix management. Key features were marketing phases at the beginning and the end of the project, dynamic conceptual growth of the instrument during its design phase within the project, and free interactions among all the team members including OEM suppliers.

For the final field trial marketing phase, several manufacturers and users of steel and aluminum sheet set up meetings at their laboratories for demonstrations of the new instrument to their personnel. At these meetings, specimens brought in by the industrial personnel were tested "blind". Our results agreed with their fundamental tensile results to within the expected errors in tensile measurements.

As a result of successful development of the instrument, an instrument company is now negotiating for production licenses.

NOTICE OF PATENT APPLICATIONS

A U.S. patent has been awarded for the stress measurement technique. Three applications for texture measurement and one for an integrated design for texture and stress measurements have been filed with the U.S. patent office. NIST has filed a related patent application, non-conflicting.

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